TEST WIRE FOR HIGH VOLTAGE POWER SUPPLY CROWBAR SYSTEM

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Abstract

The klystron microwave amplifier tubes used in the Low Energy Demonstration Accelerator (LEDA) and to be used in the Accelerator Production of Tritium (APT) plant have a strict upper limit on the amount of energy which can be safely dissipated within the klystron's vacuum envelope during a high voltage arc. One way to prevent damage from occurring to the klystron microwave amplifier tube is through the use of a crowbar circuit which diverts the energy stored in the power supply filter capacitors from the tube arc. The crowbar circuit must be extremely reliable. To test the crowbar circuit, a wire that is designed to fuse when it absorbs a predetermined amount of energy is switched between the high voltage output terminals. The energy required to fuse the wire was investigated for a variety of circuits that simulated the power supply circuit. Techniques for calculating wire length and energy are presented along with verifying experimental data.

Introduction

To operate the LEDA portion of the APT project, 1.0 MW and 1.2 MW CW klystron amplifiers supply RF to the accelerator cavities.[1] Separate high voltage power supplies operated at 95 kV, 21 A provide power to each klystron amplifier.[2]

The klystron amplifiers used in LEDA have a strict upper limit to the amount of energy that can safely be dissipated within the klystron's vacuum envelope during a high voltage arc. One way to prevent any damage from occurring to the klystron amplifier is through the use of a crowbar circuit as shown in Figure 1.

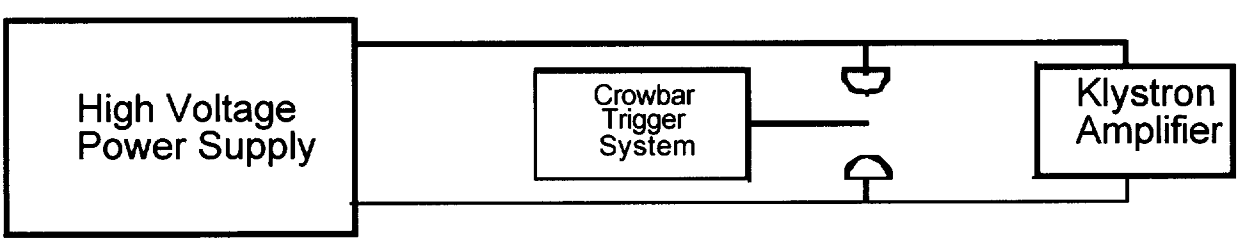

Figure 1. Block diagram of Power Supply, Crowbar, Klystron system.

The crowbar circuit will divert the energy stored in the power supply filter capacitors from the tube arc, preventing any damage to the klystron. If the klystron is not

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14. ABSTRACT
The klystron microwave amplifier tubes used in the Low Energy Demonstration Accelerator (LEDA) and to be used in the Accelerator Production of Tritium (APT) plant have a strict upper limit on the amount of energy which can be safely dissipated within the klystrons vacuum envelope during a high voltage arc. One way to prevent damage from occurring to the klystron microwave amplfier tube is through the use of a crowbar circuit which diverts the energy stored in the power supply filter capacitors from the tube arc. The crowbar circuit must be extremely reliable. To test the crowbar circuit, a wire that is designed to fuse when it absorbs a predetermined amount of energy is switched between the high voltage output terminals. The energy required to fuse the wire was investigated for a variety of circuits that simulated the power supply circuit. Techniques for calculating wire length and energy are presented along with verifying experimental data.

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protected by the crowbar circuit and an arc occurs, small wires within the klystron will fuse, rendering the klystron useless.

To test the crowbar circuit, a wire is place between the positive and negative terminals of the power supply in place of the klystron amplifier shown in Figure 1. The test wire is designed to fuse after absorbing a predetermined amount of energy. A properly operating crowbar will short the power supply before the wire reaches its melting point. If the crowbar is not operating properly, the wire will melt, indicating an operating deficiency in the crowbar circuit.

Some RF vacuum tube amplifiers have had restrictions on the allowable action of the arc current, where the action is defined as the time integral of the square of the current. Therefore, crowbar testing methods were developed to measure the action in a simulated klystron arc. The fusing action of a test wire is a physical quantity independent of the length and the circuit it is in. When testing a crowbar for its ability to limit action, a wire of any length can be used as long as it has the required fusing action. Using a wire of any length will not be sufficient with the klystrons used on the LEDA project because the klystron manufacturers have specified the maximum arc energy for a given arc voltage rather than the arc action. A specific test wire volume is needed to meet the energy restriction on the klystron amplifiers.

Physical Analysis

For any solid piece of wire, the heat required to raise the temperature is equal to the change in internal energy plus loss of energy to the surroundings. Therefore,

$$dU = dq + dE_{loss} \tag{1}$$

where dU is the incremental change in internal energy, dq is the incremental change in heat energy, and dE_{loss} is the incremental change in energy loss to the surroundings. If the heating of the wire occurs in a short enough amount of time, then the system is adiabatic, implying dE_{loss} is zero. For $dE_{loss} = 0$, equation 1 reduces to

$$dU = dq = mC_p(T)dT \tag{2}$$

where m is the mass of the wire, $C_p(T)$ is the specific heat capacity, and dT is the incremental change in temperature. Integrating and substituting ρAl for m, where ρ is the density, A is the cross-sectional area, and l is the length, equation 2 becomes

$$\Delta U = \rho Al \int_{T_o}^{T_f} C_p(T)dT \tag{3}$$

where the specific heat capacity can be approximated with a power series and ΔU is the change in internal energy of the wire.

Applying the first law of thermodynamics to the system,

$$dE = dQ - dW \tag{4}$$

in which dE, dQ, and dW are the incremental change in energy, heat transfer from the wire, and work done on the wire, respectively. Under the assumption that the system is adiabatic, equation 4 reduces to

$$dE = -dW \tag{5}$$

where $-dW$ is equal to Pdt (where P is the power dissipated in the wire, i.e. $i^2(t)R(t)$ or $v(t)i(t)$). Since there is no change in kinetic or potential energy of the wire, $dE = dU$. Therefore, setting equation 5 equal to equation 2 and making the substitution for $-dW$ and m we have

$$Pdt = \rho Al\, C_p(T)dT \tag{6}$$

After integrating, equation 6 becomes

$$\int_{t_o}^{t_f} Pdt = \rho Al \int_{T_o}^{T_f} C_p(T)dT \tag{7}$$

Therefore, equation 3 is a valid means for calculating the amount of energy dissipated in a wire.

Experiment

A schematic showing the circuit used to test the wires is given in Figure 2. Equation 3 was used to calculate energy required to fuse for various wires of differing gauge and length. Along with equation 2, the equations used to model the experiment is as follows:

$$\frac{dV_c(t)}{dt} + \frac{1}{C}\frac{V_c(t)}{r(T)} = 0 \tag{8}$$

$$r(T) = \left(\frac{\rho_o l}{A}\right)\{1 + \alpha(T - T_o)\} \tag{9}$$

where $V_c(t)$ is the capacitor voltage, C is the capacitance, $r(T)$ is the test wire resistance, T_o is the starting temperature, ρ_o is the resistivity of copper at T_o, and α is the temperature coefficient of resistivity.

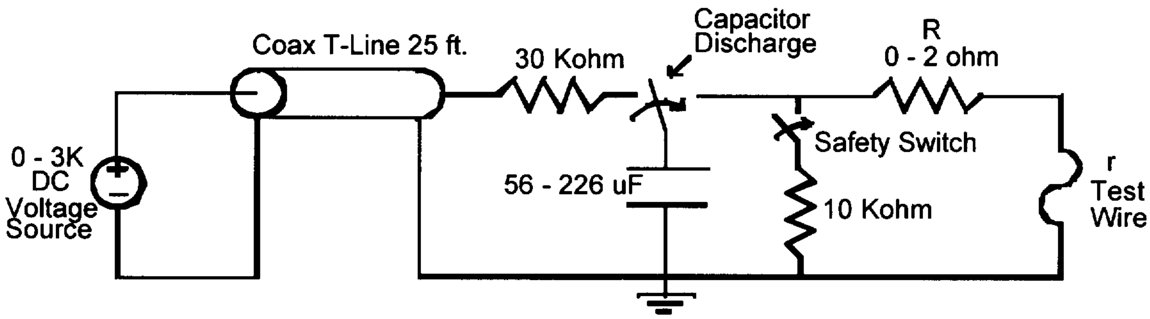

Figure 2. Schematic of Test Wire Circuit.

When modeling the wire, current values were chosen such that the time to fuse was kept under 1 ms. This allowed the adiabatic approximation to still be valid under experimental conditions to insure as little error as possible. The results of these experiments are given Table I. The data shows that equation 3 is a valid means of obtaining a good engineering approximation of the dimensions of the wire that requires a designated amount of energy to fuse. Plots of the experimental and calculated energy for a 35 gauge wire is given in Figures 3 and 4. Table I and Figures 3 and 4 show that the energy to fuse the wire is dependent only on the volume.

Table I. Test Wire Results.

Gauge	Length (m)	Capacitance (uF)	Voltage (V)	Series Resistance (ohm)	Calculated Energy (J)	Experimental Energy (J)
30	0.095	226	650	0	20	32
30	0.095	226	1800	1	20	34
30	1.000	226	1500	0	210	218
35	0.302	170	600	0	20	25
35	0.302	226	750	1	20	24
35	0.302	170	1200	2	20	22
35	1.000	112	1200	0	66	68
35	1.000	112	1350	1	66	69
35	1.000	112	1500	2	66	69
36	0.384	170	500	0	20	21
36	0.384	112	800	1	20	19
36	0.384	112	1000	2	20	22
36	1.000	170	900	0	52	59
36	1.000	170	1100	1	52	57
36	1.000	170	1300	2	52	58

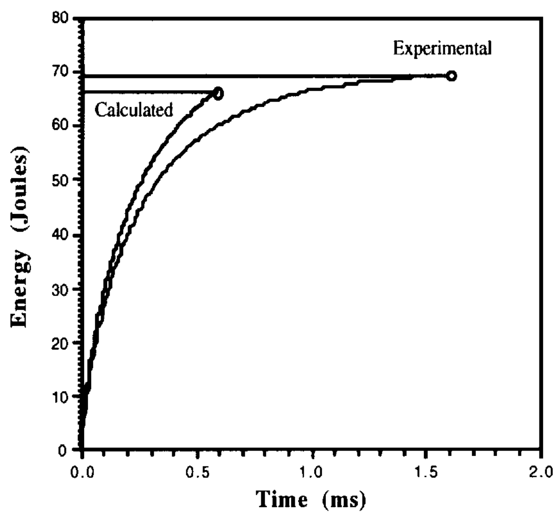

Figure 3. Energy, 35 Gauge, 1 Meter.

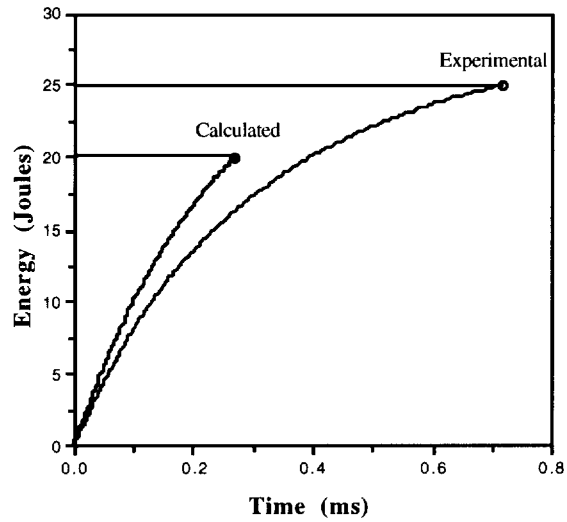

Figure 4. Energy, 35 Gauge, 0.302 Meter.

Although the energy constraints of the klystron are met by specifying the volume of the wire, modeling the arc voltage in addition to the energy would be a more complete way to test the crowbar. The voltage across an arc in a klystron can be approximated as a constant voltage drop for currents less than 1 kA.[3] Since the wire resistance increases as its temperature increases, a wire will not produce a constant voltage drop for a constant current. However, if the current through the arc or through the test wire decreases with time, then the voltage across the wire may be relatively constant. A wire volume can be chosen such that it meets the energy constraints as well as meeting the initial arc voltage drop.

Klystron arc voltage drops are determined by the internal structure of the klystron. This voltage along with an estimate of the initial arc current can be used to determine the cold resistance of the test wire as

$$\frac{\rho_o l}{A} = \frac{V_{arc}}{I_{arc_0}} \tag{10}$$

where V_{arc} is the arc voltage and I_{arc_0} is an estimated value of the initial arc current. Equation 10 and equation 3 can be used to create simultaneous length *vs.* area curves where the intersection point is the volume needed to meet the energy constraint and the length and area to meet the arc voltage requirement. A graph showing the length *vs.* wire gauge (function of the wire area) is given in Figure 5. Three possible arc voltages imply three different length curves. These curves are simultaneously graphed against a length curve for a test wire with a 20 J fusing energy. From these curves it is possible to choose a wire gauge and length needed to sufficiently test the crowbar.

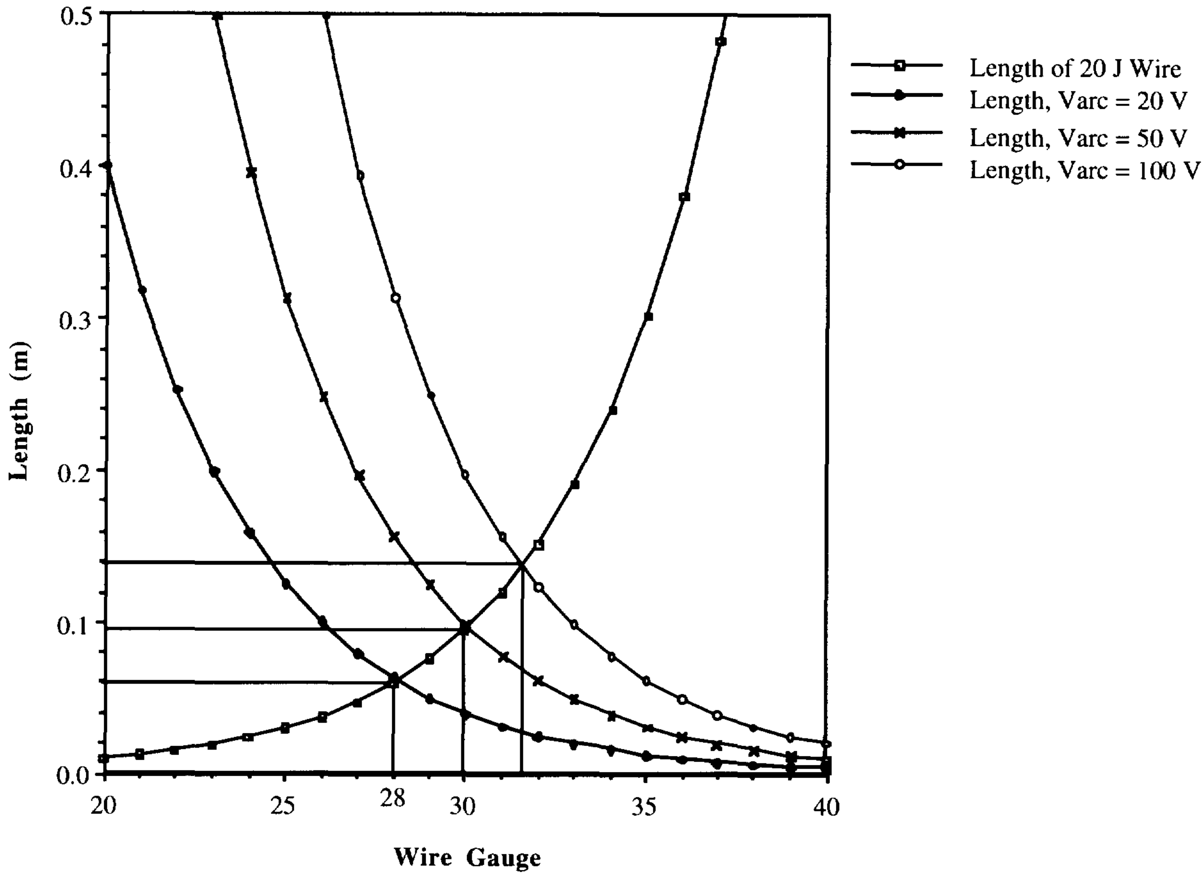

Figure 5. Two constraints on test wire dimensions.

Conclusion

The constraints on the klystron amplifiers used on LEDA and to be used on APT have changed from restrictions on the action to the energy of a klystron arc. A different method for determining test wire dimensions was developed and tested. This method is based on equating the klystron arc energy to the wire fusing energy while at the same time equating the arc voltage to the initial test wire voltage drop.

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